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# 순환적 최적우선탐색을 이용한 배전계통의 정전복구

## (Service Restoration In Distribution Networks Using Cyclic Best-First Search)

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## 요 약

정전복구 문제는 배전계통에서 고장이 발생한 겨우 사고 구간 이후의 비 고장 정전구간내의 부하를 적절한 스위칭을 통하여 인접된 건전피더로 빠른 시간 내에 절체 시키는 것이며 이때 방사상 선로구성, 전압, 전류 등의 제약조건들이 만족되어야 한다. 본 논문에서는 건전피더들이 고장 발생 직후 계통으로 공급하여야 할 부하의 총량을 규정하는 함수와 순환적 최적우선탐색을 이용하여 사고 발생 시 단지 정전의 복구뿐만 아니라 부하의 균등화까지도 함께 수행되는 효율적인 정전복구 알고리즘을 제시한다. 제시되는 알고리즘은 건전피더들이 고장 발생 직후 계통으로 공급하여야 할 부하의 총량을 규정하는 함수로부터 각 피더들이 공급하여야 할 목표치를 제안하고 또한 지수의 목적 값을 만족하는 스위칭을 찾기 위하여 순환적 최적우선 탐색법을 이용한다. 본 논문에서는 제시한 알고리즘을 실제로 서울의 K지사에서 윤용하고 있는 108모선에 적용하여 결과를 도출 했으며 그 결과 제안된 알고리즘을 이용할 경우에 적은 탐색 횟수로 정전이 복구됨과 동시에 건전 선로간의 부하가 균등화되었음을 입증하였다.

## Abstract

Service restoration is an emergency control in distribution control centers to restore out-of-service area as soon as possible when a fault occurs in distribution networks. Therefore, it requires fast computation time and high quality solutions for load balancing. In this paper, a load balance index and heuristic guided best-first search are proposed for these problem. The proposed algorithm consists of two parts. One is to set up a decision tree to represent the various switching operations available. Another is to identify the most effective the set of switches using proposed search technique and a feeder load balance index. Test results on the KEPCO's 108 bus distribution system show that the performance is efficient and robust.

Key Words : Service Restoration, Load Balancing, A Load Balance Index, Cyclic Best First Search

## 1. INTRODUCTION

Electric distribution networks maintain radial structure with normally closed sectionalizing switches along a feeder and normally open

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interfeeder tie switches for proper protection coordination. For every tie switch closed, another sectionalizing switch is opened. Under feeder faulted conditions, switches are used for fault isolation and service restoration. The resulting feeders must remain radial, without any violations of branches loading and voltage limits. Because of these requirements, the problem of service restoration is a very complicated mixed-integer, non-linear optimization problem. Since there are a numbers of switches in a practical distribution networks, the problem appears to be best solved by heuristic search methods. Heuristic approaches do not guarantee optimal solutions, but they lead to sub-optimal solutions that are technically acceptable. Many heuristic algorithms dealing with feeder restoration have been presented.

Taylor et al. [1] proposed a switch exchange type heuristic method to determine the network configuration for overloads, voltage problem, and for load balancing simultaneously. Its solution scheme sets up a decision tree which represents the various switching operations available, and a best-first search and heuristic rules are used to find feasible switching operations. Wu et al. [2] extended the method proposed by Taylor et al by developing explicit exhaustive method that solves the problem of overloads, phase current unbalance, service-restoration, and maintenance. This method is to set up a feasible switching options tree which represents possible switching options under constraint of radial structure. Evaluation functions and heuristic rules are used to find feasible switching operations.

In this paper, the authors present a heuristic service restoration algorithm considering load balancing based on an effectiveexhaustive search method. Its main steps have been implemented in two stages. First stage is to set up a sub-tree that was presented by Wu et al. [2]. Second stage is to identify the most effective the set of switches using proposed search technique called "cyclic best-first search" and a feeder load balance index. This procedure favors solutions with feeder load balancing when feeder faults are restored. Test results on the KEPCO's 108 bus distribution system show that the performance is efficient and robust.

## 2. DESCRIPTION OF DEVELOPED FEEDER LOAD BALANCE INDEX

When feeder faults are detected, the loads in the isolated feeder section are energized by transferring these load to adjacent feeders. If adjacent feeders are already overloaded, the load must be transferred to another adjacent feeders. Therefore, when loads are transferred, it must be distributed to adjacent feeders whose actual load are less than their projected loads. In this paper, to distribute loads in proportion to feeder nominal capacities, the authors presents feeder load balance index. This index extents heuristic index proposed by Taylor et al. [1] by considering feeder load balance during service restoration. The whole process is as follows.

$$FL_i = FNC_i \times \frac{\sum_{i \in K} SL_i}{\sum_{i \in U} TAC_i} \tag{1}$$

$$LI_i = FL_i - SL_i \tag{2}$$

$$LI_{sum} = |LI_1| + |LI_2| + |LI_3| + \ldots\ldots + |LI_i| \tag{3}$$

FLi : Projected load of feeder i (MVA)
LIsum : Feeder load balance index
SLi : Actual load in feeder i (MVA)
TACi : Nominal capacities in transformer i (MVA)
FNCi : Nominal capacities in feeder i (MVA)
U : Set of transformer
K : Set of feeder

During service restoration, the object in distributing feeder loadings with respect to their nominal capacities in the proportional manner is to minimize feeder load balance index.

In this paper, The service restoration considering load balance is to find feasible switch pairs for minimizing feeder load balance index with cyclic best first search.

## 3. SOLUTION ALGORITHM

The proposed search scheme starts by constructing sub-tree that was suggested in Wu et al. [2] in order to decrease searching space, and finding feasible switching operation with a cyclic best-first search and feeder load balance index.

### 3.1 Constructing the sub-tree

Under the constraint of the radial structure in the load transfer process, closing a normally open tie switch should follow the opening of a complementary normally closed sectionalizing switch. Therefore, if n tie switches are closed, then n sectionalizing switches has to be opened.

Figure 1 shows a sample distribution networks [3] consisting of three feeders with three normally opened tie switches and thirteen normally closed sectionalizing switches.

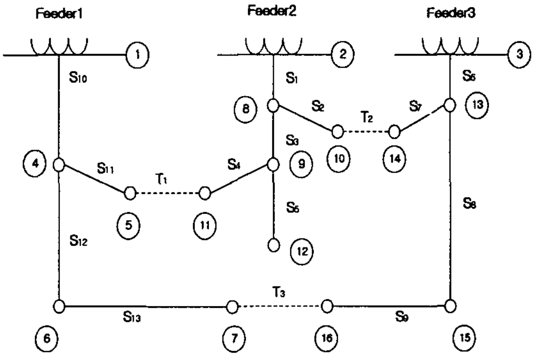

Figure 1. Three-feeder example system

If feeder section S1 experiencing an fault, then the amount of load on isolated feeder section must be transferred to feeder 1 and/or 3 without creating an overload on either of these feeders. To transfer load at node 11 from feeder 2 to feeder 1, the notation (T1, S4) is used to denote the operation of closing switch T1 and opening switch S4, henceforth. Feasible (close, open) switching options can be found by searching sectionalizing switches. When each tie switch of the isolated feeder section is closed, a complementary sectionalizing switch to be opened is found by searching from the tie switch, and moving upstream along the faulted feeder to its source; the circuit breaker of the isolated feeder section.

Figure. 2 shows a searching path for finding feasible switching options when feeder 2 is overloaded.

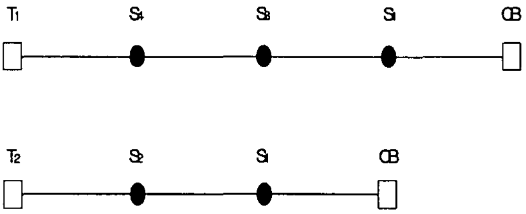

Figure 2. Main search paths for example system

If the amount of load on isolated feeder sectionis transferred to only feeder 1, then T1 and either S4, S3 or S1constitute a switching pair. So feasible switching options are expressed as {(T1, S4), (T1, S3), (T1, S1)}, and one of switching options would be a solution for transferring the isolated feeder section.

Similarly, the amount of load on isolated feeder section may be transferred to feeder 1 and 3 simultaneously by choosing one of following feasible switching options {(T1, S4), (T2, S2)}, {(T1, S4), (T2, S1)}, {(T1, S3), (T2, S2)}, {(T1, S3), (T2, S1)}, {(T1, S3), (T2, S2)}. But when T1 and T2 are used simultaneously, the switching option {(T1, S1), (T2, S1)}is not a feasible one due to radial structure constraint.

If the results of these feasible options are examined, then the corresponding sub-tree of figure.3 is obtained. In figure.3, both T1 and T2 are tie switches of isolated feeder section and dotted line represents switching options.

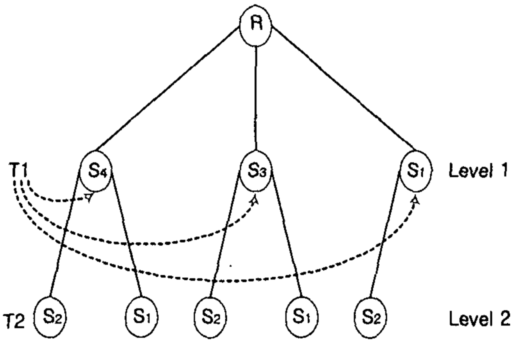

**Figure 3. Sub tree with two backup feeders**

An exhaustive search evaluates all feasible switching options of the above sub-tree and it guarantees optimal solution. But this is probably not realizable for large sub-tree because of heavy computation. On the other hand, by using heuristic search, time and effort can be saved by finding reasonable solution promptly. There are usually three heuristic search ways to find optimal(or near-optimal) switching pairs on the above sub-tree : depth-first, breadth-first, best-first. The advantage of the best-first search usually, but not always, yields solution faster than any other heuristic search. But the problem is that it does not always give the optimal solution: unexplored path would have given an optimal solution. To overcome this defect, the new methodology (so called cyclic best-first search) is presented in this paper. This methodology is based on best-first search. But, by using cyclic methodology, it can usually find more effective solution than best-first search. As an example for a best-first search, consider figure 4, where node ① is the start node and node ⑫ is a goal node. Node ① is expanded into its children node ②, ③, ④, ⑤. Since the losses of node ② is less than other nodes, node ② is chosen for expansion. This is continued until a goal node has been found.

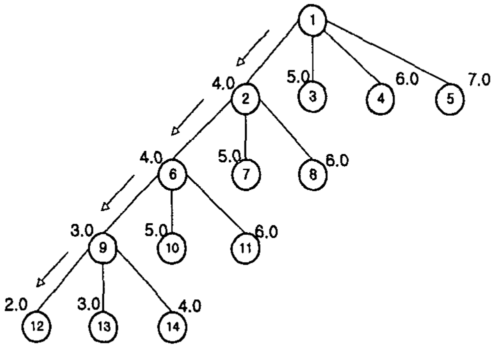

**Figure 4. An example of best-first search**

In the end, nodes {①, ②, ⑥, ⑨, ⑫ }are found by best-first search. By always expanding the most likely node, it is possible to get to a goal node or a solution quickly. But this procedure achieves the trade-off between optimality and computational speed. It is possible that unexplored path would have yielded a solution. Therefore, optimality is sacrificed for the sake of increased speed in best-first search. But, in cyclic best-first search, with circulatory reevaluating the unexplored nodes and path, more effective solution for feeder load balance could be found. Although the search space of cyclic best-first search is slightly larger than that of best-first search, the computation difference is negligible due to using heuristic based sub-tree. The cyclic best-first search process is as follows:

**First step** : nodes are selected by using best-first search.

**Second step** : Constructing the reversed sub-tree and a search is proceed by using best-first search.

Reversed sub-tree is constructed by reversing levels of sub-tree that was previously constructed. As an example, consider figure 5, the level-4 of the sub-tree in first step becomes the level-0 of the reversed sub-tree in second step, and the level-3 in first step becomes the level-1 in second step. After reversed sub tree is constructed, a best-first search is used to select near-optimal nodes in a reversed sub-tree.

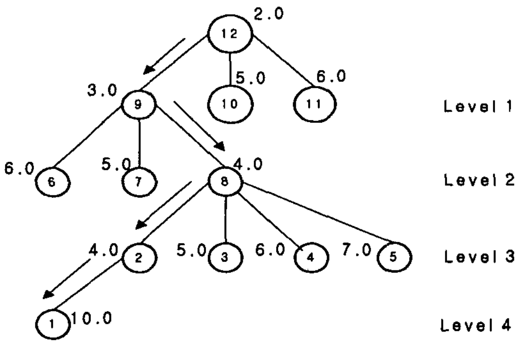

**Figure 5. Second step of best-first search**

In the second step of best-first search, nodes in each level are evaluated on condition that nodes in the lower levels are already chosen by the first step of best-first search. As an example, node ⑨ is selected on condition that nodes ①, ②, ⑥, are already determined from first step. Similarly, node ⑧ in level-2 is selected on condition that nodes ②, ① are already determined from first step.

In the first step of best-first search, the nodes in level-2 are evaluated on condition that node ⑨ in level-3 and node ⑫ in level-4 are not selected by expansion. On the contrary, in second step, nodes ⑨,⑫ were already selected before evaluating nodes in level-2, and nodes ②, ① were also determined from first step. Due to using near-optimal solution from first step, more effective solution can be found in second step. After the second step of best first search, a new nodes { ⑫, ⑨, ⑧, ②, ①} are selected.

## 4. TEST RESULT

The distribution network for KEPCO 108 bus system is used to demonstrate the validity and effectiveness of the proposed algorithm. The network consisting of two feeders with 108busbars and 14 tie switches as shown in figure.6. The total load are 72.27[MW], 32,78[MVAR] . Table 1 shows initial feeder loadings

**Table 1. Feeder loadings for 108 bus system**

| Feeder loadings [MVA] | | | | | | |
|---|---|---|---|---|---|---|
| Feeder 1 | Feeder 2 | Feeder 3 | Feeder 4 | Feeder 5 | Feeder 6 | Feeder 7 |
| 14.47 | 5.17 | 13.04 | 8.38 | 14.34 | 9.88 | 13.80 |

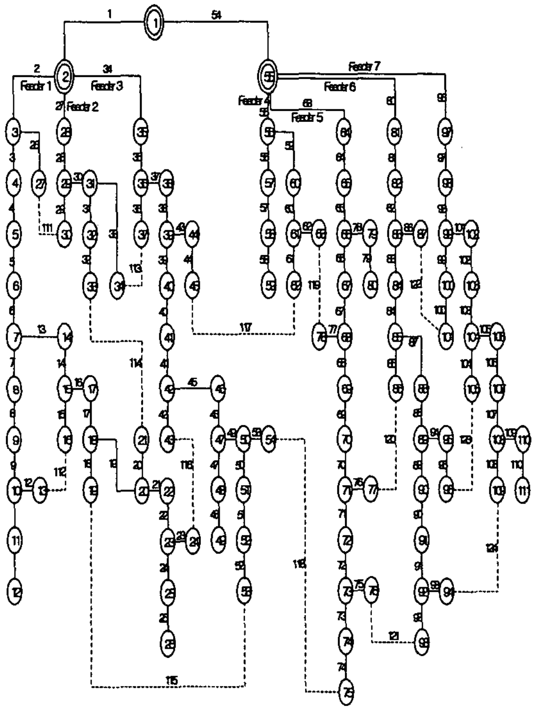

**Figure 6. Initial configuration of 108 bus system**

### ○ FAULT ON FEEDER SECTION 80

When feeder fault is detected on section 80, The first step of best-first search for initial sub-tree is shown in figure 7. Initial sub-tree level is defined by T114, T111, T117, T118, T119, T124, T123, T122, T115, T116, T118 sequentially due to the different voltage across.

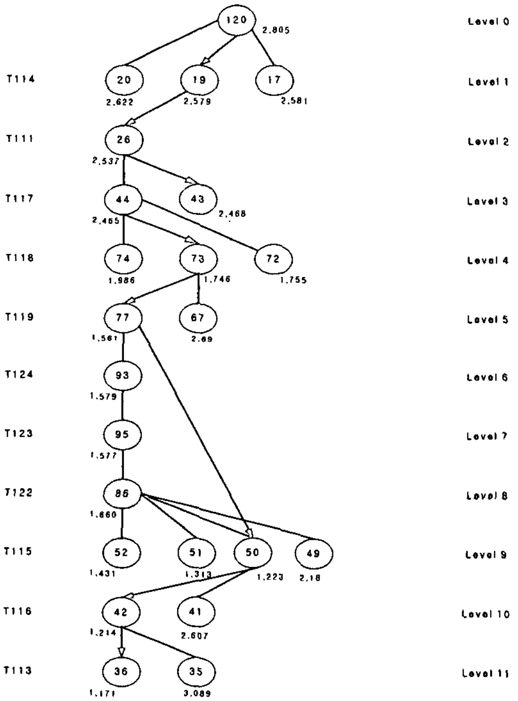

Figure 7. First step of best-first search for restoration on fault line section 80

In figure 7, the selected (close, open) switching pair for level 1 is (T114, 19) and feeder balance index is 2.579 for the switching operation. In the process of checking nodes of each level, if checked nodes would increases index then the rest of unchecked nodes are ignored and searching proceeds to next level. By pruning of the most unlikely nodes, this procedure makes it possible to get a solution much faster even if it deep down in the tree. After the first step of best-first search, selected (close, open) switching pairs are {(T114,19), (T111,26), (T117,44), (T118,73), (T119,77), (T115,50), (T116,42), (T113,36)}. This solution seems feasible but it is only locally optimal, because the first step of best-first search dose not examines all the possible nodes. Therefore, it is possible that unexplored path would have presented more feasible solution. Thus, to find more feasible solution, reversed sub-tree is constructed by reversing the level of sub-tree that was constructed in first step. The second step of best-first search is executed in figure 8.

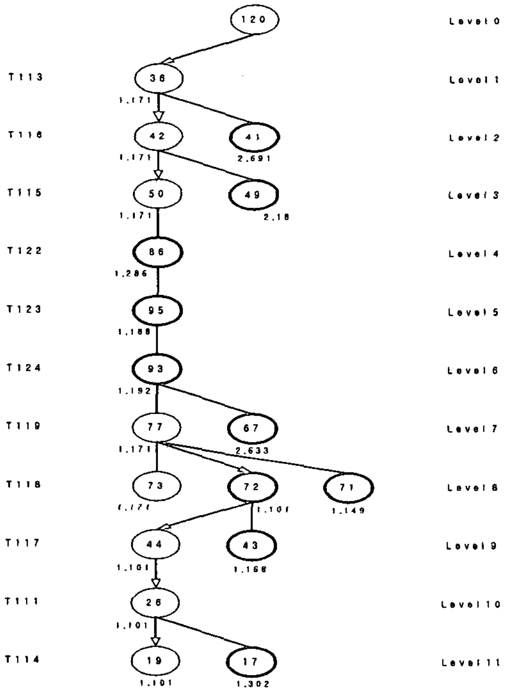

Figure 8. Second step of best-first search for restoration on fault line section 80

After the second step of best first search, switching pairs{(T114,19), (T111,26), (T117,44), (T118,72), (T119,77), (T115,50), (T116,42), (T113,36)} are selected to minimize feeder balance index. Comparing feeder loadings before service restoration with those of after service restoration is presented as below table 2 and 3.

**Table 2. Feeder loadings before service restoration when T 120 is closed to energize isolated section**

| Feeder loadings [MVA] | | | | | | |
|---|---|---|---|---|---|---|
| Feeder 1 | Feeder 2 | Feeder 3 | Feeder 4 | Feeder 5 | Feeder 6 | Feeder 7 |
| 14.47 | 5.17 | 13.04 | 8.38 | 26.06 | 0 | 13.80 |

**Table 3. Feeder loadings after service restoration when T 120 is closed to energize isolated section**

| Feeder loadings [MVA] | | | | | | |
|---|---|---|---|---|---|---|
| Feeder 1 | Feeder 2 | Feeder 3 | Feeder 4 | Feeder 5 | Feeder 6 | Feeder 7 |
| 13.17 | 11.29 | 13.04 | 11.70 | 17.91 | 0 | 13.80 |

The above comparison indicates that loadings on feeder 5 is decreased after service restoration, therefore loadings on isolated feeder section after fault are distributed in proposition to adjacent feeder nominal capacities.

## 5. CONCLUSION

In this paper, a new heuristic algorithm and feeder load balance index was presented for service restoration considering feeder load balance in distribution networks. The proposed search algorithm adopts the concept of sub-tree proposed by reference [2] and utilizes cyclic best-first search and feeder load balance index developed by the authors. Cyclic best-first search is using best-first search that gets a solution much faster even if it lies deep down in the tree. And, by using revered sub tree, it compensates best-first search for not obtaining the best solution every time. Feeder load balance index is presented in order to distributing feeder loadings with respect to their nominal capacities in the proportional manner. Test results on the KEPCO's 108 bus distribution system show that the performance is efficient and robust.

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